

Orientation discrimination in 5-year-olds and adults tested with luminance-modulated and contrast-modulated gratings

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We compared thresholds for discriminating orientation by 5-year-olds and adults for first-order (luminance-modulated) and second-order (contrast-modulated) gratings. To achieve equal visibility, we set the contrast for each age and condition at a fixed multiple of the contrast threshold for discriminating horizontal from vertical gratings. The minimum tilt that could be discriminated from vertical was four to five times larger in 5-year-olds than in adults, even when the noise was removed from the first-order stimuli and amplitude modulation increased to 0.90. Thresholds at both ages were significantly worse (1.2–1.5 times worse) for second-order modulation than for equally visible first-order modulation, and 5-year-olds were equally immature for both types of pattern. Together, the findings suggest that orientation discrimination is slow to develop and worse for second-order than first-order patterns in both children and adults.

Keywords: visual development, orientation discrimination, first-order, second-order, children, adults

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Introduction

Adults are very sensitive to small differences in orientation, typically measured by determining the minimum amount of tilt required to detect that the orientation of a line or grating has changed from some reference orientation. Estimates of threshold in central vision range from 0.4° to 3° difference in orientation, with the result dependent on the nature of the task, the reference orientation, the spatial frequency, and the line length (Burr & Wijesundra, 1991; Dupont et al., 1998; Faillenot, Sunaert, VanHecke, & Orban, 2001; Orban, Dupont, Vogels, Bormans, & Mortlemans, 1997; Vandebussche, Vogels, & Orban, 1986; Vogels & Orban, 1986; but for a much higher threshold when contrast is very low, see Hess, Ledgeway, & Dakin, 2000).

Even newborns show some ability to discriminate orientation. Specifically, after being habituated to a square-wave grating with an orientation of 45° or 135°,

newborns look longer at the novel orientation when the two orientations are presented side by side, but not when they are presented sequentially, likely because of the added memory component in the sequential task (Atkinson, Wattam-Bell, Anker, & Tricklebank, 1988; Slater, Morison, & Somers, 1988). By 1 month of age, infants can discriminate oblique orientations differing by 90° when the stimuli are presented sequentially (Maurer & Martello, 1980), and by 3 months of age (youngest tested) infants can discriminate stimuli oriented at 5° versus 15° (Bornstein, Krinsky, & Benasich, 1986). To our knowledge, there have been no behavioral studies testing finer discriminations in infancy. Nor have there been any studies of the development of orientation discrimination after infancy.

Developmental changes in behavioral measures of orientation sensitivity likely reflect changes in the orientation tuning of underlying mechanisms. These orientation-sensitive mechanisms involve both the primary visual cortex (area V1) and a network of areas in the extrastriate

ventral stream including areas V2, V3, V4, and TEO. Evidence for the importance of these areas comes from physiological studies of orientation tuning in animals (Hubel & Wiesel, 1968; Vanduffell, Tootell, Schoups, & Orban, 2002; Vogels & Orban, 1990, 1991, 1993, 1994), ablation and behavioral studies in animals (De Weerd, Peralta, Desimone, & Ungerleider, 1999), and imaging studies in humans (Dupont et al., 1998; Larsson, Landy, & Heeger, 2006). For example in monkeys, single cell recordings reveal cells tuned to orientation in areas V1 and V2 (Vogels & Orban, 1991), but their sensitivity is reduced by combined lesions to V4 and TEO (De Weerd et al., 1999). Cells in V1 code orientation based on direct input to simple cells from LGN (Hubel & Wiesel, 1962) and/or via inhibitory or excitatory interactions among V1 cells (reviewed in Das, 1996).

Studies of orientation discrimination mainly have used stimuli with orientation defined by variations in luminance (first-order cues). However, it is well documented that the human visual system is able to detect objects defined by image attributes other than luminance, such as texture, in which there is no change in mean luminance. The ability to perceive objects defined by these second-order cues applies to both spatial vision (Allard & Faubert, 2006; Ellemberg, Allen, & Hess, 2004; Hess et al., 2000; McGraw, Levi, & Whitaker, 1999; Prins & Kingdom, 2003; Sutter, Sperling, & Chubb, 1995; Wilson, 1999) and the perception of motion (Badcock & Derrington, 1985; Baker & Hess, 1998; Cavanagh & Mather, 1989; Chubb & Sperling, 1988; Wilson, 1999).

Models of first-order processing typically involve linear filters, akin to simple cells in the primary visual cortex (Movshon, Thompson, & Tolhurst, 1978). Models of second-order visual processing typically involve a separate “filter–rectify–filter” mechanism in which the outputs of linear filters tuned to the spatial frequency of the carrier stimulus undergo a nonlinear rectification and then are pooled by larger second-stage linear filters tuned to the orientation and spatial frequency of the second-order modulation (Chubb & Sperling, 1988; Wilson, 1999). Most of the evidence supporting separate first-order and second-order mechanisms comes from psychophysical studies of motion perception in visually normal human adults and children (e.g., Ellemberg, Lewis, et al., 2003, 2004; Ledgeway & Smith, 1994; Nishida, Ledgeway, & Edwards, 1997), in human amblyopes (Ellemberg et al., 2005; Simmers, Ledgeway, Hess, & McGraw, 2003), and in brain-damaged humans (Plant & Nakayama, 1993; Vaina & Cowey, 1996). These psychophysical results are supported by converging results from neuro-imaging and evoked potential studies in humans (Dumoulin, Baker, Hess, & Evans, 2003; Ellemberg, Lavoie, et al., 2003) and from physiological studies in cats (Mareschal & Baker, 1998, 1999; Zhou & Baker, 1993).

Similarly, recent reports have provided evidence of distinct first-order and second-order mechanisms underlying spatial vision in humans (Allard & Faubert, 2006;

Allen, Hess, Mansouri, & Dakin, 2003; Graham & Sutter, 1996, 1998; Larsson et al., 2006; Lin & Wilson, 1996; McGraw et al., 1999; Prins & Kingdom, 2003; Schofield & Georgeson, 1999, 2003). Although there is ample evidence for interactions between first-order and second-order mechanisms, most agree that the interactions are either weak or incomplete (Allen et al., 2003; Cruickshank & Schofield, 2005; Ellemberg, Allen, et al., 2004; Morgan, Mason, & Baldassi, 2000; Schofield & Georgeson, 1999; Smith, Clifford, & Wenderoth, 2001), indicating that the two types of signals are processed by independent mechanisms that likely combine, at least to some degree, at a later stage of processing (Allard & Faubert, 2006). However, the issue is by no means resolved. Rather than independent mechanisms, some have argued that differences in perception for first-order versus second-order stimuli represent nothing more than different responses along a single continuum, even at the early stages of processing (e.g., Benton, 2004; Bischof & Di Lollo, 1990; Hock & Gilroy, 2005).

Little is known about the sensitivity of first-order versus second-order mechanisms to orientation. Several studies have examined various aspects of orientation perception with first-order and second-order stimuli including studies of repulsion- and attraction-tilt illusions (Smith et al., 2001; Wenderoth, Clifford, & Wyatt, 2001), tilt aftereffects (Cruickshank & Schofield, 2005), interactions between orientation of a second-order envelope and orientation of its carrier (Dakin, Williams, & Hess, 1999; Morgan et al., 2000), and sensitivity to global orientation with the individual elements equated for local orientation sensitivity (Allen et al., 2003). Although these studies examined various factors influencing the perception of orientation, none varied orientation to measure thresholds.

Only two published studies have compared local orientation discrimination for first-order and second-order stimuli. One study (Lin & Wilson, 1996) found that the minimum tilt away from vertical that adults can discriminate is, on average, 2.3 times worse for second-order gratings than for first-order gratings. However, these differences may have been attributable to poorer visibility of the second-order stimuli. When the stimuli were equated for detectability and retested in two observers at short (33 ms) or longer (500 ms) exposure times, the difference in orientation threshold was still present in both observers at the short duration but only in one of the two observers at the longer exposure duration. Lin and Wilson (1996) argue that worse thresholds for second-order stimuli than for first-order stimuli at the briefer durations is consistent with the prediction that extra time is required for the additional rectification and filtering operations proposed for the processing of second-order stimuli (Chubb & Sperling, 1988; Wilson, 1999).

A second study (Hess et al., 2000) measured local orientation discrimination for first-order and second-order stimuli with exposure times of 500 ms. Each of the two participants tested had poorer orientation discrimination

for second-order than for first-order Gabors. Specifically, orientation discrimination thresholds for first-order Gabors improved systematically up to a maximum as amplitude modulation was increased and were 1.5 times better than orientation discrimination thresholds for second-order Gabors at maximum amplitude modulation. One might expect such a difference in thresholds because psychophysical studies of spatial lateral interactions suggest that the orientation tuning of neurons responding to second-order stimuli is broader than that of neurons responding to first-order stimuli (Elleberg, Allen, et al., 2004). Other than these behavioral studies, virtually nothing is known about the separability of mechanisms nor the tuning characteristics for first-order versus second-order orientation discrimination.

One purpose of this study was to provide the first measure of orientation discrimination in children after infancy. A second purpose was to investigate more thoroughly the orientation discrimination thresholds of adults for first-order versus second-order gratings that had been equated for visibility. A third purpose was to compare orientation discrimination thresholds in children and adults to determine if children are differentially immature for first-order versus second-order gratings. We chose to test 5-year-old children because we have found this to be the youngest age at which children produce reliable psychophysical thresholds using traditional two-alternative forced-choice procedures (Ahmed, Lewis, Elleberg, & Maurer, 2005; Elleberg, Lewis, et al., 2003, 2004; Elleberg, Lewis, Liu, & Maurer, 1999), and because it is the only age during childhood for which sensitivity to first-order and second-order stimuli has been measured for any aspect of vision (Elleberg, Lewis, et al., 2003, 2004).

In this study, children and adults were shown a circle filled with 1 c/deg vertically oriented stripes and made a forced-choice decision as to whether the top of the stripes was tilted toward the right or left. Each participant was tested once with first-order stimuli and once with second-order stimuli. If orientation discrimination was more immature at 5 years of age for one type of stimulus, the findings would support the notion of separate mechanisms for the discrimination of first-order and second-order orientation. For example, sensitivity to orientation defined by second-order stimuli might be slower to develop because, according to “filter–rectify–filter” models, it involves more stages of processing (Chubb & Sperling, 1988; Wilson, 1999).

Methods

Participants

The participants were 24 adults (mean age = 20 years, range 18–25 years) and 24 five-year-olds (± 3 months). None of the subjects had a history of eye problems, and all

met our criteria on a visual screening examination. Specifically, adults had a linear letter acuity (Lighthouse Visual Acuity Chart) of at least 20/20 in each eye without optical correction, worse acuity with a +3 diopter add (to rule out hypermetropia of greater than 3 diopters), fusion at near on the Worth four dot test, and stereo acuity of at least 40 arcsec on the Titmus test. The 5-year-olds met the same criteria except that they were required to have a visual acuity of at least 20/25 when tested with the Good-lite Crowding cards (Good-lite, catalogue # 1010). We relaxed the criteria for children because letter acuity is still immature at 5 years of age (Simons, 1983; reviewed in Maurer & Lewis, 2001). An additional three adults and three 5-year-olds were excluded from the final sample: the three adults and one 5-year-old for not passing visual screening, one 5-year-old for not wanting to complete the task, and one 5-year-old because of experimenter error.

Apparatus and stimuli

The stimuli were generated by a Macintosh G3 computer by means of VPixx 1.82 software™ and were displayed on a Sony Trinitron Multiscan 200-g monitor, 35° wide by 27° high when viewed from a distance of 50 cm. The monitor had a frame rate of 75 Hz and a pixel resolution of 1024 × 768. A picture of a rabbit was attached to the right side of the monitor and a picture of a lion to the left side to aid the children in their judgments of right versus left (see the Procedure section).

The stimuli consisted of static first-order (luminance-modulated) and second-order (contrast modulated) 1 c/deg vertical sinusoidal gratings in a circular aperture with a diameter of 10° on a grey background (see Figure 1). All stimuli consisted of static two-dimensional random noise (called the carrier), the luminance of which was binary. Each noise element subtended 2 × 2 arcmin and was assigned independently with a probability of 50% to be either “light” or “dark.” Michelson contrast of the noise before its modification by the sinusoidal grating was 41% for first-order stimuli and 23% for second-order stimuli. The first-order stimulus was created by adding the noise carrier to a luminance-modulated sinusoidal grating of 1 c/deg. The amplitude of the luminance modulation (Michelson contrast) was defined as

$$\text{amplitude modulation} = (L_{\max} - L_{\min}) / (L_{\max} + L_{\min}), \quad (1)$$

where L_{\max} and L_{\min} are the maximum and minimum luminances, respectively, averaged over adjacent pairs of noise dots.

The second-order stimulus was created by multiplying the carrier by a luminance-modulated sinusoidal grating (e.g., Elleberg, Lavoie, et al., 2003; Smith & Ledgeway, 1997). This produced a sinusoidal modulation of the

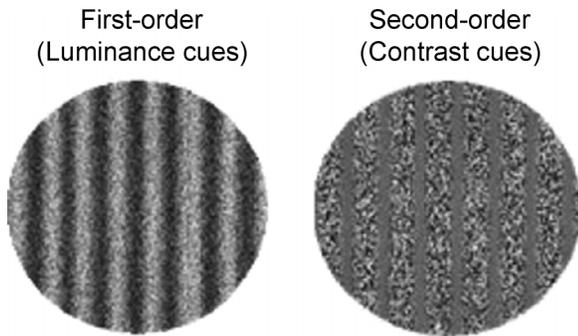


Figure 1. The stimuli used to measure tilt discrimination based on luminance cues (left) and contrast cues (right). Because the mean luminance of adjacent stripes in the stimulus on the right is identical, perception cannot depend on luminance cues. Amplitude modulation has been increased for illustration purposes.

contrast of the carrier. The stimulus consisted of a series of alternating regions of higher and lower contrast between noise dots, with every region having the same mean luminance. The amplitude of the contrast modulation was defined as

$$\text{amplitude modulation} = (C_{\max} - C_{\min}) / (C_{\max} + C_{\min}), \quad (2)$$

where C_{\max} and C_{\min} are the maximum and minimum mean local contrasts (Michelson) in the stimulus.

The space-average luminance of the stimuli and background were maintained at 16 cd/m^2 . Gamma-correction was verified by means of a Minolta LS-100 photometer. The luminance contrast of the first-order images was linearly related to the voltage of the z axis. Using the same procedure as Smith and Ledgeway (1997), we calibrated the second-order images to ensure that gamma-correction was accurate with respect to the characteristics of these stimuli. Specifically, we measured the local luminance values of the stimulus and adjusted the gamma-correction factor to eliminate any differences in luminance between the high and low contrast regions of the envelope. The correction factor was checked regularly throughout the study. Further, small noise dots (2×2 arcmin) were used so that the second-order stimuli would not contain detectable local luminance cues (Smith & Ledgeway, 1997). Note that it was necessary to set the Michelson contrast of the noise dots at 41% for first-order stimuli and 23% for second-order stimuli in order to eliminate any differences in luminance between the high and low contrast regions of the second-order envelope and to equate mean luminance of the first-order and second-order stimuli. In the Discussion section, we consider the possible effects of this difference on the results.

To achieve equal visibility across conditions, we first measured threshold contrast in different groups of 12 five-year-olds (± 3 months) and 12 adults (mean age = 20 years,

range 19–30) for (1) discriminating whether the first-order stimulus was horizontal or vertical and (2) making a similar discrimination for the second-order stimuli. We then set the amplitude modulation in the main study at 4.5 times the mean threshold contrast for each age and condition. (A multiple of 4.5 was the greatest multiple that did not exceed the maximum value of 100% amplitude modulation in any of the conditions.) In a second preliminary study involving four adults (mean age = 22 years, range 22–23) and eight 5-year-olds (± 3 months), we verified that those values were appropriate by determining that orientation thresholds did not change systematically when the amplitude modulation was increased or decreased by 25%. Two adults performed the orientation discrimination task (see the Procedure section) for all three amplitude modulations ($4.5 \times$ threshold and $4.5 \times$ threshold $\pm 25\%$) for first-order stimuli and two for second-order stimuli. In 5-year-olds, we could test only two of these values for the second-order condition ($4.5 \times$ threshold and $4.5 \times$ threshold $- 25\%$) because 4.5 times threshold resulted in 0.98 amplitude modulation and adding 25% would have exceeded the maximum amplitude modulation of 1. For consistency, we tested only two amplitude modulations in the first-order condition: $4.5 \times$ threshold and $4.5 \times$ threshold $+ 25\%$. We chose to add rather than subtract 25% to best verify that the chosen value represented asymptotic performance. Four children performed the orientation discrimination task for the first-order conditions and four for the second-order conditions.

The results of this second preliminary study showed that at both ages and for both types of stimuli, subjects' performance was consistent across amplitude modulation. This indicates that subjects would not have performed better had we chosen different values. Thus, the amplitude modulation for each condition and age in the main experiment was set at 4.5 times the contrast threshold for discriminating horizontal versus vertical for that condition and age: 0.27 and 0.63 for adults, and 0.26 and 0.98 for children tested with first-order and second-order stimuli, respectively.

Procedure

The procedures were explained and informed consent was obtained from the adults and from parents of the 5-year-olds. The experimental protocol was approved by the McMaster Research Ethics Board. Subjects were tested binocularly in a room illuminated only by the computer monitor and were adapted to the lighting conditions prior to the test. The subject was seated 50 cm from the stimuli with the chin positioned on a chin-rest. Parents sat in the testing room out of their child's sight and were asked to remain silent throughout the testing.

Subjects were instructed to fixate a 1° black circle in the center of the screen that appeared between trials. On each trial, subjects were shown a patch of stripes for 1 s and

were asked to judge whether the top of the stripes was tilted to the left or right. The experimenter said: *In this game, a black dot will appear and you have to look right at the black dot. Then the black dot will disappear and you will see a circle filled with stripes. It's your job to tell me whether the top of the stripes are tilted to the "left" toward the lion or to the "right" toward the rabbit.* The experimenter pressed a key to begin a trial and entered the responses by means of the keyboard. The experimenter also watched the participant's eyes continuously to ensure that he or she was looking at the center of the screen, provided regular reminders to do so, and began a trial only when the participant was looking in the middle of the screen. Participants each completed two runs, one with first-order stimuli and one with second-order stimuli. Half the participants at each age were tested first with first-order stimuli and half were tested first with second-order stimuli. The procedure began with a demonstration, criterion trials, and a practice run with the same type of stimulus (first-order or second-order) that was to be tested first.

Demonstration trials

The demonstration consisted of two trials with the maximum tilt (45°), one with the stripes tilted to the right and one with the stripes tilted to the left. For each demonstration trial, the experimenter asked the participant to choose whether the stripes were tilted left or right and demonstrated the direction of tilt with fingers tilted to the left or to the right.

Criterion trials

The purpose of the criterion was to verify that subjects understood the task. Subjects were presented with a block of four trials, each of which had the same tilt (45°) as the demonstration trials, with left and right tilts presented in a random order. To be included in the study, participants had to judge the direction of tilt correctly on all four trials within a block. Subjects had three chances to meet this criterion and all subjects did so, usually within the first block.

Practice run

Thresholds were calculated using a maximum-likelihood threshold estimation procedure (ML-TEST) in which the tilt on the first trial was set at 45° and the value presented on each subsequent trial was the best estimate of the subject's threshold based on the history of the run (Harvey, 1997). Threshold was defined as the minimum tilt away from vertical needed to discriminate orientation accurately. Specifically, each measurement of threshold was stopped at the value corresponding to 82% correct responses with a confidence interval of 95% that

the estimate of threshold was accurate within ± 0.1 log units. Each subject was given a full practice staircase. The experimenter was aware of the stimulus presented during each interval, and, if the subject began making mistakes on "easy" trials, provided feedback and encouragement.

Test of thresholds

The procedure for measuring each threshold was identical to that for the practice run, except that the experimenter was unaware of the direction of tilt on each trial and provided encouragement but no feedback. Demonstration and test phases were then repeated for the second condition (first-order or second-order). The median number of trials per staircase was 60 for 5-year-olds and 73 for adults, with no prespecified limit on the maximum. Subjects were given as many breaks as necessary and all subjects completed the testing protocol in one session that lasted no more than 1 hr.

Data analysis

The data set contained two orientation discrimination thresholds (one for each of the two pattern types) for each of the 24 adults and 24 five-year-olds. An outlier procedure recommended by Kirk (1990) was used to replace deviant scores. Specifically, each threshold was converted to a Z score using the mean and standard deviation for that age and pattern type. Z scores greater than $+2.5$ or less than -2.5 were replaced with the original group mean (i.e., the mean threshold for the condition before the removal of outliers). Three data points were replaced, one from an adult tested with the second-order pattern and two from 5-year-olds, one tested with the first-order pattern and one tested with the second-order pattern. All subsequent analyses were conducted using this revised data set. Effect size was estimated using simplified procedures to calculate Cohen's d statistic where effect sizes of <0.15 , <0.40 , <0.75 , <1.10 , and >1.45 represent negligible, small, medium, large, and huge effect sizes, respectively (Cohen, 1992; Thalheimer & Cook, 2002).

Results

As shown in Figure 2, orientation discrimination thresholds were worse in 5-year-olds than in adults for both first-order and second-order patterns. Specifically, 5-year-olds were 4.7 times worse than adults for first-order patterns (adult mean = 0.93° ; 5-year-old mean = 4.36°) and were 4 times worse for second-order patterns (adult mean = 1.36° ; 5-year-old mean = 5.46°). A mixed ANOVA with

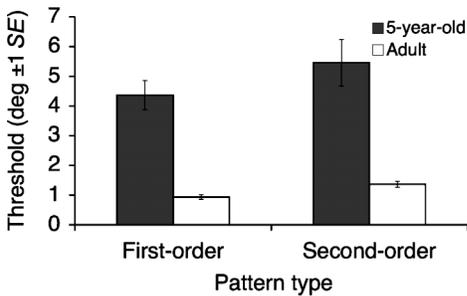


Figure 2. Mean orientation discrimination thresholds (± 1 SE) for 5-year-olds (grey bars) and adults (white bars) tested with first-order patterns (left bars) and second-order patterns (right bars).

one between-subjects factor (age) and one within-subjects factor (pattern type) revealed a main effect of age, with children worse than adults, $F(1,46) = 38.72$, $p < .0001$, $d = 1.83$, and a main effect of pattern type, with thresholds worse for second-order than for first-order patterns, $F(1,46) = 8.22$, $p < .01$, $d = 0.84$. However, there was no significant interaction between age and pattern type, $F(1,46) = 1.60$, $p > .20$, $d = 0.37$, indicating that 5-year-olds were equally immature for the two pattern types.

Control study

To evaluate whether the immaturities were caused by the low amplitude modulation for the first-order stimuli and/or by the noise in the stimuli, we also tested different groups of 20 adults (mean age = 21 years, range 18–29 years) and 20 five-year-olds (± 3 months), each with four first-order stimuli: (1) with noise and an amplitude modulation that was high (0.76) or low (0.26) as it was in the main experiment; and (2) sine wave gratings without noise and an amplitude modulation that was high (0.90) or low (0.26) as in the main experiment. The procedure was identical to that described in the main experiment except that each participant contributed four thresholds. Half of the subjects were tested on both noise conditions first and the other half on both no-noise conditions first. Within the noise or no-noise condition, half were tested with low amplitude modulation first and the other half with high amplitude modulation first.

Three data points were replaced because of deviant scores: one from an adult tested in the noise, high amplitude condition and two from 5-year-olds, one tested in the noise, high amplitude condition and one tested in the no-noise, high amplitude condition. Subsequent analyses were conducted using this revised data set.

As shown in Figure 3, orientation discrimination thresholds were worse in 5-year-olds than in adults for all conditions. Specifically, 5-year-olds were 3.8 times worse than adults for noise, low amplitude (adult mean = 1.01° ; 5-year-old mean = 3.84°); 3.9 times worse for noise, high amplitude (adult mean = 0.92° ; 5-year-old mean = 3.60°);

4.5 times worse for no-noise, low amplitude (adult mean = 0.73° ; 5-year-old mean = 3.28°); and 4.1 times worse for no-noise, high amplitude (adult mean = 0.85° ; 5-year-old mean = 3.52°). A mixed ANOVA with one between-subjects factor (age) and two within-subjects factors (noise and amplitude modulation) revealed a main effect of age, $F(1,38) = 64.87$, $p < .0001$, $d = 2.61$. However, there was no effect of noise, $F(1,38) = 0.93$, $p > .30$, $d = 0.31$; no effect of amplitude modulation, $F(1,38) = 0.002$, $p > .90$, $d = 0.01$; and there were no significant interactions ($p > .30$ for all, d values ranging from 0.02 to 0.31), indicating that 5-year-olds' immaturities in orientation discrimination, at least for first-order stimuli, were not caused by the low amplitude modulation or by the noise in the stimuli.

Discussion

We found that adults' orientation discrimination thresholds were 0.9° for a first-order grating and 1.4° for an equally visible second-order grating. These values are similar to those obtained from previous studies using similar methods. Using high contrast lines sufficiently long to yield optimal results and a task that required identifying the direction of tilt off the main axes (vertical or horizontal), others have obtained orientation thresholds in adults typically ranging from about 0.4° to 3° (Dupont et al., 1998; Lin & Wilson, 1996; Orban et al., 1997; Vandebussche et al., 1986).

Adults performed significantly worse (1.5 times worse) for a second-order than for an equally visible first-order pattern presented for a relatively long exposure time (1 s). Better performance for the first-order stimuli was not likely caused by the higher contrast of the noise dots, before amplitude modulation, for first-order than for second-order stimuli (41% vs. 23%, respectively). The visual system does not resolve luminance differences in the carrier when the dots are as small as 2×2 arcmin (Smith & Ledgeway, 1997), and the effects of contrast on orientation discrimination saturate for contrasts above

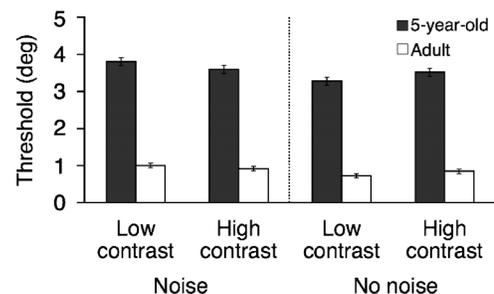


Figure 3. Mean orientation discrimination thresholds (± 1 SE) for 5-year-olds (grey bars) adults (white bars) tested with first-order patterns. The patterns had either noise (left panel) or no noise (right panel) and were of either low or high contrast.

10–20% (Hess et al., 2000). Similarly, in the control study of the present experiment, orientation discrimination was not affected by changes in contrast from 26% to 90%. Moreover, the visibility of the first-order and second-order stimuli created by amplitude modulation of each set of noise dots was equated in the preliminary experiments.

The differences in orientation discrimination for first-order versus second-order stimuli complement those of Hess et al. (2000) who also found orientation discrimination in the two participants to be 1.5 times worse for a second-order Gabor than for a first-order Gabor presented for 500 ms when each was at optimal amplitude modulation. The findings also complement those of Lin and Wilson (1996) who reported poorer orientation thresholds for a second-order than for an equally visible first-order grating in the two adults tested with short exposure times (33 ms) but in only one of two adults tested with long (500 ms) exposures times. Similarly, in the current study, some adults (3 of 20) did not show the typical pattern of worse tilt thresholds for second-order than for first-order stimuli.

Our finding of worse orientation thresholds for second-order than for first-order stimuli does not distinguish between models postulating one versus two underlying mechanisms. One possibility is that distinct first-order and second-order mechanisms underlie orientation discrimination in human adults, and poorer orientation thresholds for second-order stimuli arise because orientation tuning is broader for second-order than for first-order stimuli (Elleberg, Allen, et al., 2004; Lin & Wilson 1996). The visual system may also be subject to more internal noise for second-order than for first-order orientation discrimination as is the case for the detection of first-order versus second-order spatial structure (Allard & Faubert, 2006). However, the finding of lower sensitivity to tilt for second-order than for first-order stimuli does not on its own establish the existence of separate mechanisms. In fact, the results are equally consistent with a unitary mechanism for orientation discrimination that is differentially sensitive to different stimulus parameters.

We also found that 5-year-olds are four to five times worse than adults at discriminating orientation both when the patterns are defined by first-order cues and when they are defined by second-order cues. The immaturities for the first-order stimuli cannot be explained by a greater influence in children than in adults of noise in the stimuli or of the low amplitude modulation: orientation discrimination thresholds for the first-order stimuli were still four times worse in children than in adults even when the noise was removed from the stimuli and amplitude modulation was increased to 0.90. Unfortunately, similar control conditions could not be tested for second-order stimuli because they require noise for their construction and amplitude modulation could not be increased because it was already close to maximum in the main experiment.

Nonvisual factors such as differences between adults and 5-year-olds in attention, criteria, and/or motivation

may have contributed to the age differences but are unlikely to account fully for the differences in thresholds. By age 5, children perform as well as adults on some psychophysical tasks that have performance demands like those in this study, namely, tasks that use two-alternative forced-choice procedures to measure thresholds. For example, studies of sensitivity to the direction of local motion indicate that thresholds of 5-year-olds are nearly adult-like for first-order (luminance-defined) stripes moving at 1.5 or 6 deg/s and for second-order (contrast-defined) stripes moving at 1.5 deg/s (Elleberg, Lewis, et al., 2003). Similarly, sensitivity to the direction of global motion tested with random dot kinematograms is mature as early as 3 years of age (Parrish, Giaschi, Boden, & Dougherty, 2005). However, we cannot rule out the possibility that children were poorer than adults in judging tilt because an accurate internal representation of vertical was required in this study and that may not be as good in children as in adults. Like explanations based on attention or motivation, such a cognitive limitation should have affected performance in all conditions and cannot account for our finding that the children, like the adults, had tilt thresholds that were 1.3–1.5 times better for first-order than for second-order stimuli, a pattern that is likely to be caused by similar neural factors at both ages. Overall, our results suggest that the neural mechanisms involved in perception of orientation are still immature at 5 years of age.

The poorer performance by 5-year-olds may be caused by immaturities in the primary visual cortex and/or by the network of areas in the extrastriate ventral stream known to be involved in orientation sensitivity (e.g., De Weerd et al., 1999; Larsson et al., 2006). Neurons in those networks may be less sharply tuned to orientation because the excitatory and/or the inhibitory mechanisms are immature. Recent evidence from postmortem examinations of human brain tissue indicates that GABAergic inhibition increases two- to threefold around 8 years of age (Boley, Jones, Pinto, & Murphy, 2005). An additional possibility is that the coding of spatial orientation within the child's visual system is subject to more internal, orientation-based noise than that of adults. Any of these factors alone or in combination might account for poorer orientation discrimination in 5-year-olds than in adults.

Under the current testing conditions, orientation discrimination thresholds for first-order and second-order patterns were equally immature in 5-year-olds and, as in adults, thresholds were poorer for second-order than for first-order stimuli. These results are unlike those of a study measuring the perception of first-order and second-order local motion in 5-year-olds and adults (Elleberg, Lewis, et al., 2003). Specifically, 5-year-olds' contrast thresholds for seeing the direction of local motion were 2.5–8 times more immature for second-order patterns than for first-order patterns, with differences in immaturity dependent on speed and/or temporal frequency (Elleberg, Lewis, et al., 2003).

Different rates of development of sensitivity to orientation defined by first-order and second-order stimuli would provide strong evidence for the existence of separate mechanisms. This is exactly what we found in the motion domain, at least under some conditions (Elleberg, Lewis, et al., 2003, 2004). However, our finding of equivalent rates of maturation in the orientation domain is consistent with postulating either one or two mechanisms. One possibility is that distinct first-order and second-order mechanisms underlie motion perception but not orientation discrimination. A second possibility is that both are mediated by separate mechanisms but, for the processing of second-order information, the parts of the ventral pathway mediating orientation discrimination mature at a faster rate than the parts of the dorsal pathway mediating sensitivity to the direction of local motion. A third possibility is that differences across studies are not attributable to differences in the mechanisms underlying the perception of orientation versus motion but rather to differences in tasks involving suprathreshold stimuli (as in this study of orientation discrimination) versus threshold stimuli (our previous study of contrast thresholds for seeing local motion). Indeed, in our preliminary study, the contrast threshold of the 5-year-olds for the discrimination of horizontal from vertical stimuli was adult-like for first-order but not second-order stimuli, whereas in the main study the tilt discrimination thresholds for suprathreshold stimuli were equally immature. Similarly, in a previous study of sensitivity to global motion which involved suprathreshold stimuli, we found that 5-year-olds were more immature for second-order stimuli than for equally visible first-order stimuli only at slow speeds (1.5 deg/s) but not at faster speeds of 6 or 9 deg/s (Elleberg, Lewis, et al., 2004). A final possibility is that differential rates of maturation for first-order versus second-order orientation are evident only for some spatial frequencies, as was the case for only some speeds in our study of global motion (Elleberg, Lewis, et al., 2004). Regardless of the explanation, it is clear that the mechanisms mediating first-order and second-order orientation discrimination are equally immature in 5-year-olds and that orientation discrimination is worse for second-order than for first-order patterns in both children and adults.

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